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MACHOs: THE PLOT THICKENS

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ABSTRACT

We discuss the implications of the recent upward revision of the LMC microlensing rate by the MACHO Collaboration. We conclude: (i) A good case for the existence of baryonic dark matter in the halo has been made; (ii) The case for the existence of cold dark matter is unaffected and still compelling; and (iii) The Galactic halo is still an excellent place to search for cold dark matter particles (e.g., axions or neutralinos).

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1 Perspective

It is now a little more than two years since the MACHO and EROS Collaborations announced their first microlensing results: one LMC event for MACHO and two LMC events for EROS [1]. At about the same time OGLE also reported microlensing events toward the bulge. at a much higher rate than expected rate [2]. Paczynski's bold idea had become reality.

The initial response to the LMC results was swift and not unexpected: The dark matter problem has been solved – it was baryons after all. A dark cloud of gloom engulfed the particle dark matter searches. After a while, sanity returned: The numbers were small and the uncertainties – both Poisson and galactic modelling – were large [3].

About a year ago MACHO [4] and EROS [5] presented detailed analyses of a big chunk of data (for MACHO the first year's data with three events toward the LMC; for EROS the same two events). Both groups concluded that the halo MACHO fraction was small, around 20%. Our independent analysis [6, 7] of the LMC and bulge data based upon extensive galactic modelling indicated the same (likelihood function peaked around a halo MACHO fraction of 15%.) WIMP hunters were very happy. However, as we and others (David Bennett especially) emphasized the uncertainties were still large and it was too early to rule out an all-MACHO halo. Moreover, others had suggested radical ideas for an all baryonic halo, e.g., gas clouds [8].

The OGLE [2] – and later the MACHO [9] – higher-than-expected bulge results provided further evidence that the bulge is actually a heavy bar, a possibility not considered in the original estimates. This has important consequences for interpreting the LMC events. A heavy bar precludes a light halo, which, for a given LMC microlensing rate, pushes down the halo MACHO fraction [6, 7].

The MACHO Collaboration has now analyzed two years of LMC data and has 8 or 7 or 6 events, depending upon selection criteria. Two year-one events have now been rejected (one turned out to be a repeater). The halo MACHO fraction is now quoted as 50% [10]. The dark cloud threatens WIMP chasers again – 50% is dangerous close to 100%.

What happened? The nearly 100 bulge events seen by the MACHO Collaboration allowed a "tune up" of their event-recognition software, and they have another full year of data. They are able to detect longer duration events – and reject repeaters – and the statistics are better.

Beware! The number of events is still small and galactic uncertainties are still large. More long duration events may be found; some candidates may be rejected, and the software may improve again – leading to higher or lower rates. It is not time for WIMP hunters to panic.

Based upon the seven MACHO LMC events, the microlensing rate toward the bulge and extensive modelling of the Galaxy, we find a likelihood function for the MACHO halo fraction which is very broad (allowing both 0 and 100%) and which achieves its maximum at around 30% (see Fig. 1). (For reference, the MACHO Collaboration bases its 50% estimate on their standard halo model, which is "light" by industry standards, leading to their higher MACHO halo fraction. In light of the large uncertainties the differences are not important.) Our likelihood function for the local density of "unknown matter" indicates that there is still

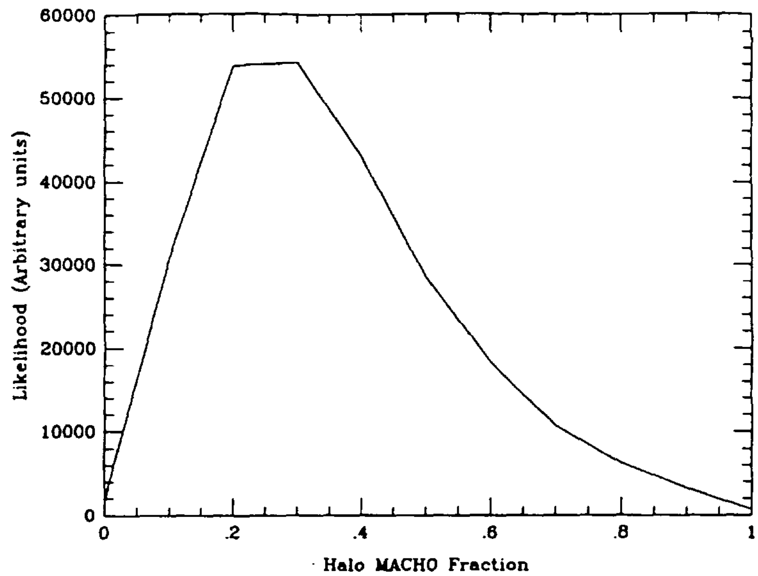

Figure 1: Monte-Carlo generated likelihood function for the halo MACHO fraction based upon the upward revision of the LMC optical depth by the MACHO collaboration [10, 11] and extensive galactic modelling (described in Refs. [6, 7]).

plenty of room for cold dark matter in our own back yard (see Fig. 2).

2 Interpretation

The MACHO Collaboration did not actually measure the MACHO fraction of the halo! They measured the frequency of microlensing toward the LMC, which can be expressed as the optical depth for microlensing – the probability that a given LMC star is being microlensed. Based upon the seven events in the two-year data set $\tau_{\rm LMC} = 2^{+1.0}_{-0.6} \times 10^{-7}$ [11].[1] *Assuming* that MACHOs are distributed as the halo material (density decreasing as r^{-2}) and that the halo MACHO fraction is constant throughout the halo, the optical depth can be used to *infer* the fraction of the halo mass contributed by MACHOs – about 50% according to the MACHO Collaboration [10, 11] or 30% according to our analysis.

If, however, MACHOs are distributed differently, the halo MACHO fraction can be much lower. For example, for a spatial density that decreases as r^{-3}, like the spheroid component of the Galaxy, the inferred MACHO fraction falls to about 10%.[2]

Further, since the distance to the LMC is 50 kpc microlensing of LMC stars cannot probe the halo beyond this. In fact, most of the optical depth is contributed by MACHOs that are between 10 kpc and 30 kpc from the center of the Galaxy (see Figure in Ref. [3]). It could be

[1]The optical depth $\tau = \frac{\pi}{4E}\sum_i \frac{t_i}{\varepsilon_i}$, where t_i is the duration of event i, E is the exposure (e.g., in star-years), and ε_i is the efficiency of detecting an event of duration t_i.

[2]Such a model is only viable if $\tau \lesssim 2 \times 10^{-7}$.

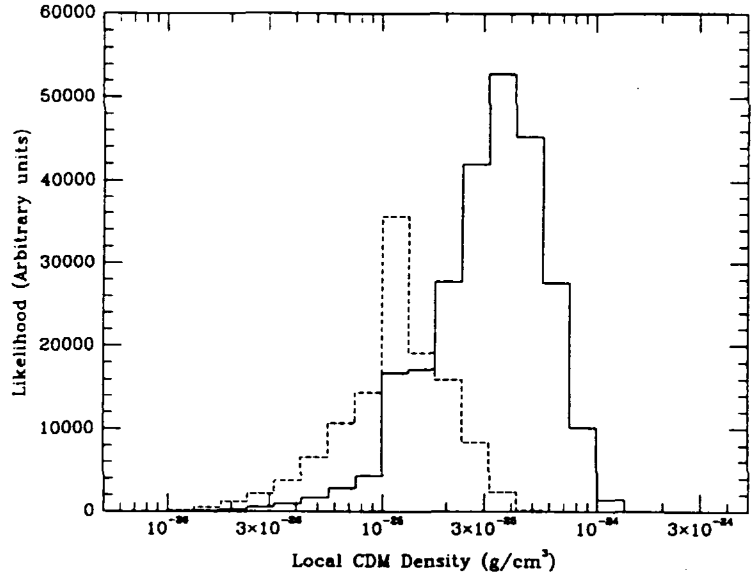

Figure 2: Monte-Carlo generated likelihood function for the local density of cold dark matter particles, assuming a spherical halo comprised of MACHOs and cold dark matter. Broken curve is the same, but with the prior that the halo MACHO fraction is greater than 60%. Note, there is good reason to believe that the halo of the Galaxy is flattened, which increases the local halo density by about a factor of two over that of a spherical halo [19].

that the inner portion of the Galaxy has a MACHO fraction of 50% and that the MACHO fraction falls off beyond this, so that something else accounts for the bulk of the halo. There is good evidence that the halo of the Galaxy extends to 100 kpc or more. (When the density decreases as r^{-2} the mass per interval of radial distance is constant.)

Even more difficult to estimate is the fraction of critical density contributed by MACHOs. As described above, the halo MACHO fraction is difficult to determine, and the fraction of critical density contributed by the dark halos of spiral galaxies is very poorly known. This is because the full extent of dark halos is not known; if halos are small $\Omega_{\rm HALO}$ could be as low as 0.05; on the other hand if halos are as large as they could be, extending to neighboring galaxies, $\Omega_{\rm HALO}$ could be 1.0.

3 Implications for Particle Dark Matter

There are a number of very good reasons to believe that the bulk of matter in the Universe exists in the form of slowly moving elementary particles left over from the earliest moments (cold dark matter), with the most promising cold dark matter candidates being the axion and the neutralino. First, the cold dark matter scenario for structure formation is by a wide margin the most successful, with supporting evidence coming from anisotropy measurements of the CBR, large redshift surveys, and numerous other observations. (By cold dark matter, we mean one of the several variants that have been discussed – cold dark matter plus hot dark matter, a cosmological constant, tilted spectrum of density perturbations, unstable tau neutrino, or very low Hubble constant [12].) While the mean density of the Universe has yet to be determined, the masses of clusters of galaxies [13] and the peculiar velocities of galaxies (including our own) [14] indicate that Ω_0 is at least 0.2, which is larger than the upper limit to what baryons can contribute that comes from primordial nucleosynthesis, $\Omega_B \lesssim 0.02h^{-2}$ [15]. (Note, this upper limit is only close to 0.2 if the Hubble constant is very small, $h \sim 0.35$. For $h \sim 0.7$, $\Omega_B \lesssim 0.04$ and virtually all cosmologists would agree that Ω_0 is greater than 0.1.) On the theoretical side, inflation predicts a critical density Universe, $\Omega_0 = 1.0$; current measurements of CBR anisotropy are consistent with the inflationary prediction [16], and measurements made in the next five years or so should decisively test inflation [17].

It should be noted that the dark halos of spiral galaxies like our own never provided evidence for nonbaryonic dark matter for the simple reason that galactic halos need not contribute more mass density than baryons can account for. On the other hand, galactic halos are – and always have been – an excellent place to search for cold dark matter particles since it is virtually impossible to keep cold dark matter out of galactic halos [18].

Within the context of the cold dark matter theory the universal fraction of matter in baryons is expected to be between 5% and 20%. The baryonic content of the halo is another matter; galactic halos probably do not provide a fair sample of the cosmos. At least some of the baryons in our galaxy have undergone dissipation – those in the disk – and it is not impossible that the bulk of the baryons have condensed into the disk, in which case the halo MACHO fraction would be smaller than the universal baryon fraction. At the other extreme, it is possible that most of the baryons in our galaxy have undergone only modest dissipation and reside in the inner portion of the halo, in which case the baryon fraction there could be 50% or so. Estimates for the plausible MACHO fraction of the inner halo range from 0% to 50% [18].

4 Finale

The MACHO, EROS, and OGLE microlensing experiments have monitored millions of stars over the past few years looking for the proverbial needle in the haystack. And they have found it – making believers of the many nay-sayers who doubted that microlensing could be detected against the background of known variable stars and unknown things that go bump in the night. The detection of microlensing represents a significant scientific achievement as well as an important new probe of the Galaxy.

It is still too early to make definitive statements concerning the composition of the Galactic halo. However, strong evidence has been presented for the existence of massive, dark objects within 30 kpc of the center of the Galaxy. The most plausible explanation is dark stars (e.g., white dwarfs or neutron stars of mass $\sim 0.3M_\odot$).

The galactic baryonic dark matter believed to exist on the basis of big-bang nucleosynthesis may well have been identified and one of the two dark matter problems may have been solved! That would be quite an achievement. (Big-bang nucleosynthesis provides a lower limit to the baryon density, $\Omega_B \gtrsim 0.01h^{-2}$, that exceeds the contribution of luminous matter, $\Omega_{\rm LUM} \simeq 0.003h^{-1}$.)

Galactic microlensing has not diminished the case for a Universe comprised primarily of cold dark matter. In fact, the inferred halo MACHO fraction suggests that much of the nearby dark matter in the Galaxy is still of undetermined composition (see Fig. 2), with cold dark matter particles leading the list of possibilities. This, together with the cosmic motivations for cold dark matter, should continue to warm the hearts of WIMP chasers and justify their heroic efforts to detect particle dark matter in our back yard.

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